VARIABLE DAMPERS FOR SEMI-ACTIVE CONTROL OF FLEXIBLE STRUCTURES

by

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Fahim Sadek[1] and Bijan Mohraz[2]

ABSTRACT

Semi-active control using variable dampers has been suggested for reducing the response of structures to different dynamic loadings. This study is concerned with examining the effectiveness of these devices for seismic applications. Three algorithms for selecting the damping coefficient of variable dampers are presented and compared. They include: a linear quadratic regulator (LQR) algorithm, a generalized LQR algorithm with a penalty imposed on the acceleration response, and a displacement-acceleration domain algorithm where the damping coefficient is selected by representing the response as a point on the displacement-acceleration plane. Two single-degree-of-freedom structures subjected to 20 ground excitations are analyzed using the three algorithms. The analyses indicate that contrary to passive dampers where an increase in damping increases the acceleration response of flexible structures, variable dampers can be effective in reducing the response. Variable dampers, however, are not efficient for rigid structures. The study also indicates that the generalized LQR algorithm is more efficient than the other two in reducing the displacement and acceleration responses. The algorithms are used to compute the seismic response of an isolated bridge modeled as a SDOF system. The results indicate that variable dampers significantly reduce the displacement and acceleration responses of the flexible structure.

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Introduction and Summary of Previous Work

Semi-active control combines the features of active and passive systems to reduce the dynamic response of structures. The control forces are developed by utilizing the response of the structure and regulated by algorithms which use the measured excitation and/or response. Semi-active systems include two categories; active variable stiffness and active variable damping. In the first category, the stiffness of the structure is adjusted to establish a non-resonant condition. In the second category, supplemental energy dissipating devices such as fluid, friction, and electrorheological dampers are modified to allow adjustments in their mechanical properties during the excitation in order to achieve further reductions in the response. In both categories, similar to passive systems, control forces are generated using the motion of the structure and like active systems, controllers monitor the feedbacks to develop the appropriate commands for selecting the stiffness or the damping coefficient of the device.

This study focuses on the use of semi-active control algorithms for structures with variable damping devices. Several investigators have found variable dampers to be effective in reducing the response of structures to different dynamic loadings. In addition to requiring a small power source, the control forces developed by these devices always oppose the direction of motion; thereby, enhancing the overall stability of the structure.

For variable dampers, the damping coefficient $c(t)$ during the response can be adjusted between upper and lower limits, c_{max} and c_{min}; i.e.,

$$c_{\min} \leq c(t) \leq c_{\max} \tag{1}$$

Several algorithms have been developed for selecting the appropriate damping coefficient during the response. Patten et al. (1993) and Sack et al. (1994) used a clipped optimal control algorithm based on the linear quadratic regulator (LQR) with a check on the dissipativeness of the control force. In other studies, Patten et al. (1994) and Loh and Ma (1994) used a bang-bang (also referred to as two-stage, bi-state, or on-off) algorithm based on the Lyapunov method to select the damping coefficient. Feng and Shinozuka (1990, 1993) used two semi-active algorithms for regulating the damping coefficient of a variable damper in an isolated bridge. One was a bang-bang algorithm where $c(t)$ is set to c_{max} when the relative displacement response divided by a referenced displacement is greater than the absolute acceleration response divided by a referenced acceleration. For the opposite case, $c(t)$ is set to c_{min}. The other algorithm was an instantaneous optimal algorithm. Kawashima and Unjoh (1994) used a displacement dependent damping model to select the damping coefficient of a variable fluid damper for a 30 m long bridge. In a later study, Yang et al. (1994) used the sliding mode control theory to design an algorithm for the variable damper suggested by Kawashima and Unjoh (1994). The idea behind the sliding mode control theory is to drive and maintain the response trajectory into a sliding surface where the motion of the structure is stable. Dowdell and Cherry (1994) used a bang-bang semi-active LQR algorithm to control the slip forces in friction dampers. Calise and Sweriduk (1994) used robust control techniques for variable damping devices and demonstrated their effectiveness in reducing the response.

In an analytical and experimental study, Symans and Constantinou (1995) developed and tested a two-stage and a variable fluid damper. For the two-stage damper, they used a base shear coefficient and a force transfer control algorithm, while for the variable damper, they employed a feedforward, a skyhook damping, a LQR, and a sliding mode control algorithm. They conducted the studies for a single- and a three-story frame under different seismic excitations. The results indicated that while variable dampers reduced the response significantly as compared to the no control case, no reduction was observed when compared to the device acting as a passive damper with a damping coefficient c_{max}.

The study by Symans and Constantinou (1995) indicates that the use of semi-active dampers in structures is inefficient when compared to passive systems. Since their study was limited to a SDOF structure with a period of 0.36 s and a MDOF structure with a fundamental period of 0.56 s, the efficiency of the device for other periods merits further investigation. This study considers a broad range of periods for which semi-active control with variable dampers may be more efficient in reducing the response. In the next sections, three semi-active control algorithms are examined to determine the effectiveness of variable dampers in reducing the seismic response.

Discussion and Analysis

Increased damping in structures allows the dissipation of a larger portion of the input energy and consequently, a further reduction in the response. The reduction, however, depends on the flexibility or rigidity of the structure. Feng and Shinozuka (1990, 1993) have reported that for isolated bridges, increased damping has opposite effects on the absolute acceleration of the girder and the relative displacement between the girder and the piers. A similar observation has been made by Sadek et al. (1996) who showed that for flexible structures (structures with periods longer than approximately 1.5 s), an increase in damping decreases the displacement response but often increases the absolute acceleration response. Reducing the absolute acceleration is important in designing structures such as hospitals, communication centers, computer and electronic rooms, etc. which house sensitive equipment that may be disrupted or damaged by large floor accelerations. Large accelerations can also cause discomfort to occupants.

To illustrate the influence of supplemental damping and structural period on the seismic response of structures, six single-degree-of-freedom structures with periods T = 0.2, 1.0, 1.5, 2.0, 2.5, and 3.0 s and a structural damping ratio β of 0.05 are used. Two supplemental passive dampers with damping ratios ξ equal to 0.05 and 0.40 were considered. The structures were subjected to a set of 20 horizontal components of accelerograms from the western United States that include a range of earthquake magnitudes, epicentral distances, peak ground accelerations, and soil conditions. The relative displacement and absolute acceleration response ratios are computed as the ratio of the peak response of the structure with the supplemental damper to the peak response without the damper. The average response ratios for the twenty records for the six structures are shown in Table 1. The table shows that for structures with $T \geq 1.5$ s, increasing the damping ratio from 0.05 to 0.40 decreases the relative displacement but increases the absolute acceleration, whereas for structures with shorter periods ($T < 1.5$ s), increasing the damping decreases both the relative displacement and absolute acceleration. Therefore, for flexible structures, better reductions in the displacement and acceleration responses may be achieved with a variable damper than with a passive damper, i.e. achieving a displacement response close to that obtained with ξ_{max} and an acceleration response close to that obtained with ξ_{min}.

Table 1. Average response ratios for six SDOF structures with passive damping

Damping ratio (1)	T=0.2 s (2)		T=1.0 s (3)		T=1.5 s (4)		T=2.0 s (5)		T=2.5 s (6)		T=3.0 s (7)	
	x_{max}	a_{max}	x_{max}	a_{max}	x_{max}	a_{max}	x_{max}	a_{max}	x_{max}	a_{max}	x_{max}	a_{max}
$\xi_{min} = 0.05$	0.81	0.82	0.81	0.83	0.81	0.84	0.84	0.88	0.86	0.91	0.89	0.95
$\xi_{max} = 0.40$	0.46	0.54	0.42	0.72	0.46	0.94	0.54	1.19	0.56	1.36	0.59	1.55

Semi-Active Control Algorithms

The governing differential equation of motion for an n-degree of freedom structure with mass matrix M, damping matrix C, and stiffness matrix K with m semi-active dampers subjected to ground acceleration $\ddot{x}_g(t)$ is given by:

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = Du(t) - M1\ddot{x}_g(t) \tag{2}$$

where the n-dimensional vector $x(t)$ represents the relative displacement, the m-dimensional vector $u(t)$ the control forces generated by the dampers, and the n-dimensional vector I the unit vector. The matrix D (m x n) defines the locations of the control forces generated by the dampers. Using the state-space representation, Equation 2 takes the form:

$$\dot{z}(t) = Az(t) + Bu(t) + H\ddot{x}_g(t) \tag{3}$$

where $z(t) = [x^T(t), \dot{x}^T(t)]$ is a $2n$-dimensional state vector. The system matrix A, and the matrices B and H are given in Soong (1990). Three semi-active control algorithms for regulating the damping coefficient of the variable dampers are considered in this study. They include:

a) Semi-Active LQR Algorithm

This algorithm, referred to herein as SA-1, is the classical linear quadratic regulator which has been extensively used for active control (Soong, 1990, Yang et al., 1992) and for semi-active control (Patten et al, 1993, 1994; Dowdell and Cherry, 1994; Symans and Constantinou, 1995) of structures. In this algorithm, the control force $u(t)$ is obtained by minimizing the following quadratic cost function over the duration of the excitation t_f (Soong, 1990):

$$J = \int_0^{t_f} [z^T(t)Qz(t) + u^T(t)Ru(t)]dt \tag{4}$$

where Q ($2n$ x $2n$) and R (m x m) are positive semi-definite and positive definite weighting matrices, respectively. Minimizing Equation 4 subject to the constraint of Equation 3 results in a control force vector $u(t)$ regulated only by the state vector $z(t)$ such that:

$$u(t) = -\frac{1}{2} R^{-1} B^T P z(t) = G z(t) \tag{5}$$

where matrix G (m x $2n$) represents the gain matrix, and matrix P ($2n$ x $2n$) is the solution of the classical Riccati equation (see Soong, 1990).

The damping coefficient of damper i at time t can be computed from Equation 5 as

$$c_i^*(t) = \frac{u_i(t)}{\dot{x}_i(t)} = \frac{\sum_{j=1}^{2n} G_{i,j} z_j(t)}{\dot{x}_i(t)}, \quad i=1,m \tag{6}$$

where $\dot{x}_i(t)$ is the relative velocity between the ends of damper i. Using the constraints in Equation 1, the damping coefficient is selected as

$$c_i(t) = \begin{cases} c_{\min,i} & c_i^*(t) \le c_{\min,i} \\ c_i^*(t) & c_{\min,i} < c_i^*(t) < c_{\max,i} \\ c_{\max,i} & c_i^*(t) \ge c_{\max,i} \end{cases} \tag{7}$$

To examine the effectiveness of this algorithm, two SDOF structures with periods T = 0.2 s and 3.0 s and a structural damping ratio β = 0.05 are considered. Each structure includes a variable damper with a damping ratio ranging from $\xi_{\min}$ = 0.05 to $\xi_{\max}$ = 0.40. The structures are subjected to the 20 ground excitations as before. In this analysis, R is a scalar set equal to $1/K$ and Q is selected as (see Wu et al., 1995)

$$Q = q \begin{bmatrix} K & 0 \\ 0 & M \end{bmatrix} \tag{8}$$

where q is a parameter reflecting the importance of the reduction in the state vector $z(t)$ or the control force vector $u(t)$. The mean response ratios for q ranging from 0 to 1.0 are plotted in Figure 1 for T = 0.2 s and in Figure 2 for T = 3.0 s. The plots indicate that for q = 0, the mean response ratios are very close to those with a passive damper with $\xi_{\min}$ = 0.05, and for $q \geq 0.5$, the mean response ratios are nearly the same as those with a passive damper with $\xi_{\max}$ = 0.40 (compare columns 2 and 7 of Table 1 and the ordinates at q = 0 and q =1 in Figures 1 and 2, respectively). For q between 0 to 0.5, the response ratios fall between those with a passive damper with $\xi_{\min}$ and $\xi_{\max}$. For the structure with T = 0.2 s (Figure 1), increasing q decreases both the relative displacement and absolute acceleration. For the structure with T = 3.0 s (Figure

2), however, increasing q decreases the relative displacement but increases the absolute acceleration. Figure 1 shows that for the structure with T = 0.2 s, a variable damper is inefficient and the use of a passive damper with a damping ratio equal to ξ_{max} is more advantageous.

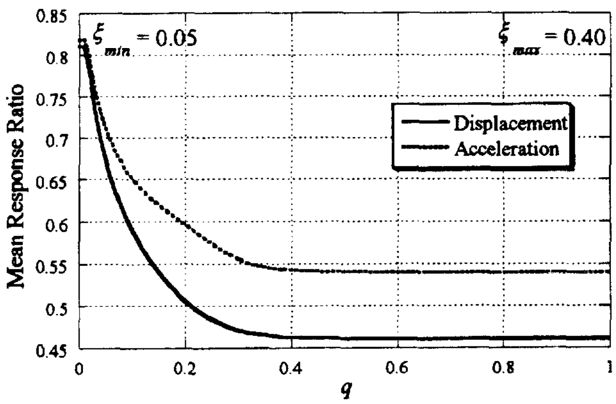

Figure 1. Mean response ratios for the structure with T=0.2 s using algorithm SA-1.

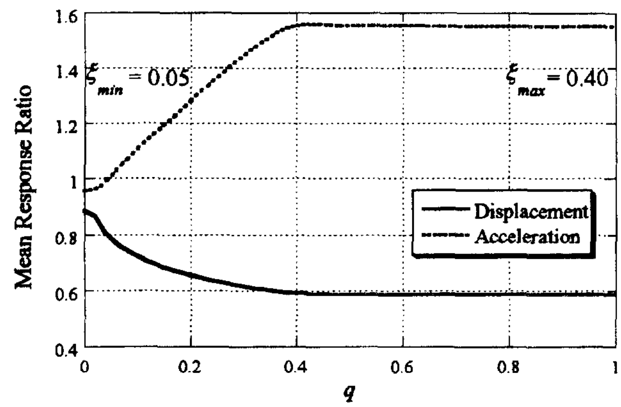

Figure 2. Mean response ratios for the structure with T=3.0 s using algorithm SA-1.

Shown in Table 2 (column 4) are the average response ratios for the structure with T = 3.0 s where q is adjusted to yield a displacement response ratio of 0.70 (q = 0.12). This ratio is selected as the baseline for comparing the responses from the three algorithms. The table indicates that, compared with a passive damper with ξ_{max} (column 3), the SA-1 algorithm increases the relative displacement by 0.11 (11%) and reduces the absolute accelerations by 0.40 (40%).

Table 2. Average response ratios for the structure (T = 3.0 s) with passive and variable dampers.

Control (1)	Passive, ξ_{min} (2)	Passive, ξ_{max} (3)	SA-1 (4)	SA-2 (5)	SA-3 (6)
x_{max}	0.89	0.59	0.70	0.70	0.70
a_{max}	0.95	1.55	1.15	0.95	1.09

b) Semi-Active Generalized LQR Algorithm

This algorithm, referred to herein as SA-2, was introduced by Yang et al. (1992) for active control of structures and is adopted for semi-active control in this study. In this algorithm, the cost function is augmented by imposing a penalty on the absolute acceleration of each degree-of-freedom to control the acceleration response of the structure. The generalized cost function has the form

$$J = \int_0^{t_f} [z^T(t)Qz(t) + \ddot{x}_a^T(t)Q_a\ddot{x}_a(t) + u^T(t)Ru(t)]dt \qquad (9)$$

in which $\ddot{x}_a(t)$ is the absolute acceleration vector and Q_a (n x n) is a symmetric positive semi-definite weighting matrix. Minimizing Equation 9 subject to the constraint of Equation 3 results in a control force vector $u(t)$ of the form

$$u(t) = -\frac{1}{2}\tilde{R}^{-1}(B^T\tilde{P} + 2B_0^T Q_a A_0)z(t) = \tilde{G}z(t) \tag{10}$$

where $\tilde{G}$ (m x $2n$) is the gain matrix and $\tilde{P}$ ($2n$ x $2n$) is the solution to the classical Riccati equation. Matrices $\tilde{P}$, $\tilde{R}$, $\tilde{A}$, $\tilde{Q}$, A_0, and B_0 can be found in Yang et al. (1992). Similar to the SA-1 algorithm, the damping coefficient of damper i at time t can be computed from Equations 6 and 7 after replacing the gain matrix G by $\tilde{G}$.

The two SDOF structures with T = 0.2 s and 3.0 s with a variable damper were analyzed using the SA-2 algorithm. The same scalar $R = 1/K$ and matrix Q (Equation 8) with $q = 0.5$ for both T = 0.2 s and T = 3.0 s are used in this example. It should be noted that $q = 0.5$ results in a response approximately the same as that using a passive damper with $\xi_{max} = 0.40$ (see Figures 1 and 2). For SDOF systems, Q_a is a scalar and equal to q_a which reflects the importance of the reduction in the state vector $z(t)$ or the acceleration response vector $\ddot{x}_a(t)$.

The mean displacement and acceleration response ratios for the two SDOF structures subjected to the 20 accelerograms for q_a ranging from 10^0 to 10^5 for T = 0.2 s and 10^3 to 10^7 for T = 3.0 s are shown in Figures 3 and 4, respectively. The figures show that the response with a variable damper is similar to that with a passive damper with $\xi_{max} = 0.40$ for small q_a (compare columns 2 and 7 of Table 1 and Figures 3 and 4, respectively). Figure 3 shows that for the structure with T = 0.2 s, increasing q_a increases both the displacement and acceleration responses and again a variable damper is not as efficient as a passive one with a damping ratio ξ_{max}. Figure 4 indicates that for the structure with T = 3.0 s, the variable damper is effective in reducing the acceleration response significantly while increasing the displacement response slightly.

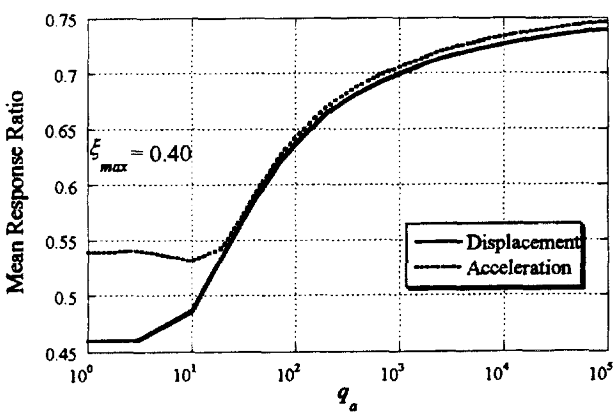

Figure 3. Mean response ratios for the structure with T=0.2 s using algorithm SA-2.

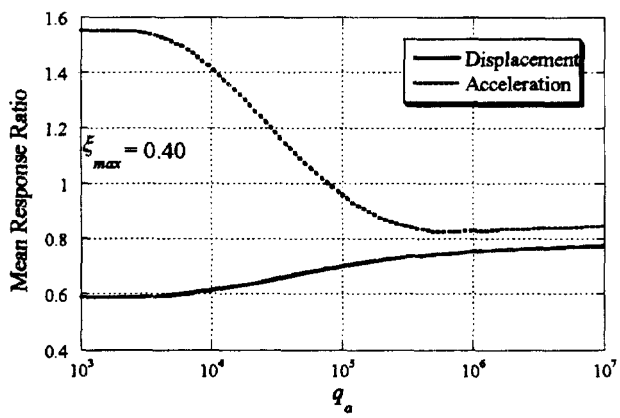

Figure 4. Mean response ratios for the structure with T=3.0 s using algorithm SA-2.

Shown in Table 2 (column 5) are the mean response ratios for the structure with T = 3.0 s where q_a is adjusted to yield a mean displacement response ratio of 0.70 (q_a = 1.0 x 10^5). The table shows that compared with a passive damper with ξ_{max} = 0.40 (column 3), the SA-2 algorithm increases the relative displacement by 11% while it decreases the absolute acceleration by 60% (the acceleration response is the same as that with a passive damper with ξ_{min} = 0.05, see column 2). This demonstrates the effectiveness of the SA-2 algorithm in reducing the response.

c) Semi-Active Displacement-Acceleration Domain Algorithm

This algorithm, referred to herein as SA-3, is a refinement of the bang-bang algorithm presented by Feng and Shinozuka (1990, 1993). The refinement assumes a displacement-acceleration domain (Figure 5) where the horizontal axis represents the relative displacement response and the vertical axis the absolute acceleration response normalized to a reference parameter Ω. The parameter Ω which has the unit of s^{-2} is used as a weighting factor to impose different penalties on the displacement and acceleration responses. At any time t, the response may be represented by a single point in the displacement-acceleration domain. The angle $\theta(t)$ between the horizontal axis and the line connecting the origin to the response point, Figure 5, is used to select the damping coefficient. This angle is:

$$\theta(t) = \tan^{-1} \frac{|\ddot{x}_a(t)|/\Omega}{|x(t)|} \tag{11}$$

A small $\theta(t)$ indicates a large displacement response with respect to the normalized acceleration and consequently requiring a higher damping coefficient. The opposite is true for a large $\theta(t)$. It is therefore desirable to assign a large damping coefficient c_{max} for small θ ($0 \le \theta(t) \le \theta_1$) and a small damping coefficient c_{min} for large θ ($\pi/2 - \theta_1 \le \theta(t) \le \pi/2$) where the angle θ_1 is yet to be determined. A linear variation of the damping coefficient with $\theta(t)$ is used for $\theta_1 \le \theta(t) \le \pi/2 - \theta_1$ (see Figure 5). Thus, the damping coefficient may be selected as follows:

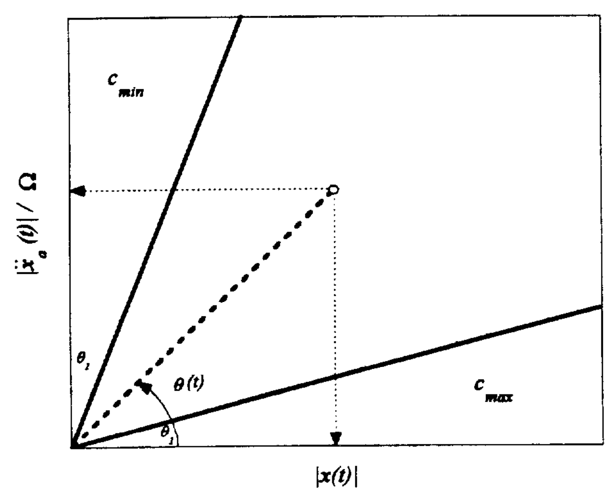

Figure 5. Displacement-acceleration domain for algorithm SA-3.

$$c(t)=\begin{cases} c_{\min} & \pi/2-\theta_1 \le \theta(t) \le \pi/2 \\ c_{\max}-\dfrac{c_{\max}-c_{\min}}{\dfrac{\pi}{2}-2\theta_1}[\theta(t)-\theta_1] & \theta_1 < \theta(t) < \pi/2-\theta_1 \\ c_{\max} & 0 \le \theta(t) \le \theta_1 \end{cases} \tag{12}$$

It may be seen from Equation 11 that increasing Ω decreases $\theta(t)$ which results in selecting a large *c(t)*. Consequently, reducing the relative displacement has priority over reducing the absolute acceleration. The opposite is true for decreasing Ω. The reference parameter Ω, therefore, reflects the importance of reduction in relative displacements or absolute accelerations. It is also noted that contrary to the first two algorithms (SA-1 and SA-2) which depend on the structure's stiffness, damping, and mass which may be affected by errors in estimating the structural properties, the SA-3 algorithm depends on the measured response only, Equations 11 and 12. This algorithm, therefore, results in a robust control system with respect to the uncertainties in estimating the structural parameters.

The two SDOF structures with T = 0.2 s and 3.0 s with variable dampers are analyzed using the SA-3 algorithm. Different values for θ_l were assumed. It was found that a θ_l between $\pi/10$ to $\pi/30$ resulted in the largest reductions in the response. The mean displacement and acceleration response ratios for the 20 records for $\theta_l = \pi/10$ and for Ω ranging from 10^1 to 10^5 for T = 0.2 s and 10^{-2} to 10^4 for T = 3.0 s are plotted in Figures 6 and 7, respectively. The figures show that for small Ω s, the response is approximately the same as that with a passive damper with $\xi_{\min} = 0.05$ and for large Ω s, the response is nearly the same as that with a passive damper with $\xi_{\max} = 0.40$ (compare columns 2 and 7 of Table 1 and Figures 6 and 7, respectively). Figure 6 shows that for the structure with T = 0.2 s, semi-active control is inefficient and that a passive damper with $\xi_{\max}$ is more advantageous.

Shown in Table 2 (column 6) are the mean response ratios for the structure with T = 3.0 s where the value of Ω is adjusted to yield a mean displacement response ratio of 0.70 ($\Omega = 8\ s^{-2}$). The table indicates that compared with a passive damper with $\xi_{\max}$, the SA-3 algorithm increases the relative displacement by 11% and reduces the absolute accelerations by 46%.

Application - Simple Bridge Model

A bridge modeled as a SDOF structure was used to assess the effectiveness of the algorithms in reducing the seismic response. The bridge is similar to that suggested by Feng and Shinozuka (1990, 1993). It has a mass of 1.02 x 10^6 kg and a hybrid control system consisting of an isolator with a stiffness 3300 kN/m and a variable damper. The damping ratio for the bridge is assumed as 2% and the damping coefficient of the variable damper varies between c_{min} = 150 kN.s/m and c_{max} = 1200 kN.s/m. The bridge was subjected to four accelerograms -- the N21E component of Taft Lincoln School Tunnel, Wheeler Ridge earthquake, 1954; the S74W component of Pacoima Dam, San Fernando earthquake, 1971; the 0 degree component of the Corralitos Eureka Canyon Road accelerogram, the Loma Prieta earthquake, 1989; and the 90 degree component of the Arleta

Nordhoff Avenue Fire Station accelerogram from the Northridge earthquake, 1994; each scaled to a peak ground acceleration of 1.0g. The results of the analyses with no control and with passive control with damping coefficients c_{min} and c_{max} are shown in Table 3 (columns 2-4) which indicate that an increase in damping decreases the relative displacements but increases the absolute accelerations.

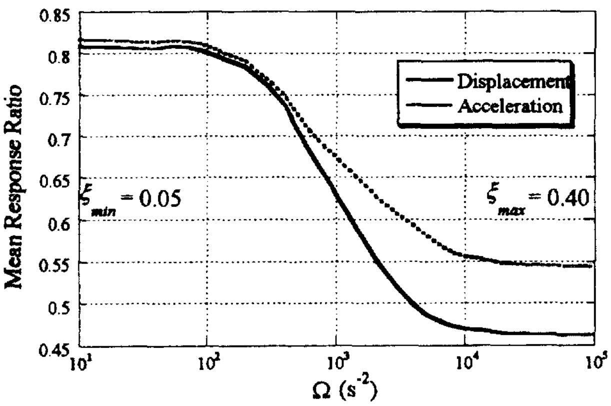

Figure 6. Mean response ratios for the structure with T=0.2 s using algorithm SA-3.

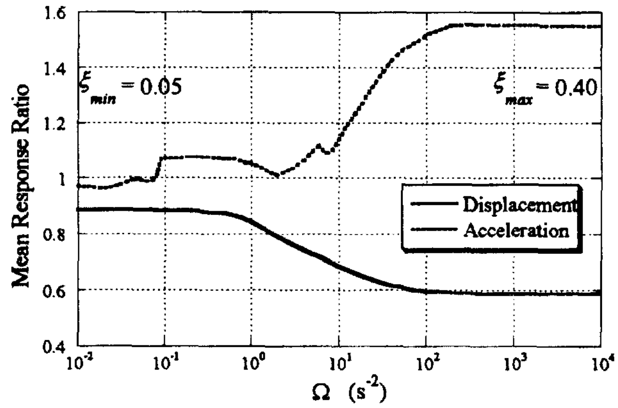

Figure 7. Mean response ratios for the structure with T=3.0 s using algorithm SA-3.

The bridge was also analyzed with a variable damper using the three algorithms. For the SA-1 algorithm, the scalar R is set equal to $1/K$ and the matrix Q is computed by Equation 8. By varying q, different combinations of displacements and accelerations are obtained. Shown in Table 3 (column 5) are the responses for q = 0.12 where it is observed that x_{max} and a_{max} are between those obtained with c_{min} and c_{max}. The bridge was also analyzed using the SA-2 algorithm with q = 0.6 (q = 0.6 resulted in a response the same as that using a passive damper with c_{max}) and different values of q_a. The results for $q_a = 3 \times 10^5$ are shown in Table 3 (column 6) where it is noted that the displacement responses are close to (or even lower than) those with c_{max} and the acceleration responses are close to those with c_{min}. The analysis with the SA-3 algorithm was carried out for $\theta_l = \pi/10$ and different Ω values. The results presented in Table 3 (column 7) are for $\Omega = 7\ s^{-2}$. Similar to the SA-1 algorithm, the responses are between those with a low and a high damping coefficient. The results in Table 3 underscore the advantage of using the SA-2 algorithm.

Table 3. Response of the bridge with no control and with passive and semi-active dampers.

Control (1)	No Control (2)		Passive, c_{min} (3)		Passive, c_{max} (4)		SA-1 (5)		SA-2 (6)		SA-3 (7)	
	x_{max} m	a_{max} g	x_{max} m	a_{max} g	x_{max} m	a_{max} g	x_{max} m	a_{max} g	x_{max} m	a_{max} g	x_{max} m	a_{max} g
Taft	0.250	0.083	0.236	0.085	0.181	0.137	0.199	0.122	0.175	0.079	0.197	0.125
Pacoima Dam	0.170	0.056	0.144	0.050	0.114	0.086	0.118	0.074	0.106	0.048	0.116	0.074
Corralitos	0.297	0.098	0.246	0.083	0.157	0.137	0.183	0.107	0.151	0.088	0.182	0.091
Arleta	0.488	0.161	0.411	0.143	0.308	0.218	0.340	0.195	0.350	0.128	0.358	0.185

Conclusions

The objective of this study was to investigate the effectiveness of variable dampers in reducing the response of structures to earthquake loading. Three semi-active control algorithms are presented and compared. They include: 1) a linear quadratic regulator (LQR) algorithm referred to as (SA-1) which has been used extensively in active and semi-active control of structures; 2) a generalized LQR algorithm referred to as (SA-2) with a penalty imposed on the acceleration response which was introduced by Yang et al. (1992) for active control and is adopted for use as a semi-active control algorithm in this study; and 3) a displacement-acceleration domain algorithm referred to as (SA-3) where the damping coefficient is selected based on the location of the response parameters on the displacement-acceleration plane.

Two single-degree-of-freedom structures were analyzed with the three algorithms using 20 accelerograms for the excitation. The results indicate that: a) variable dampers can be effective in reducing the acceleration response of flexible structures such as base-isolated and tall buildings, and isolated and cable-stayed bridges where an increase in damping adversely affects the acceleration response. Variable dampers, however, are not effective for rigid structures as compared to passive dampers; b) The SA-2 algorithm is more efficient than the other two in reducing the displacement and acceleration responses. The efficiency of this algorithm is, in most part, due to the penalty imposed in controlling the absolute acceleration response; and c) the SA-1 and SA-3 algorithms result in similar efficiency in reducing the response of SDOF structures, although the SA-3 algorithm is more robust. The three algorithms were used to compute the seismic response of an isolated bridge modeled as a SDOF structure. The results indicate that for this flexible structure, variable dampers are quite effective in reducing the displacement and acceleration responses.

Acknowledgments

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